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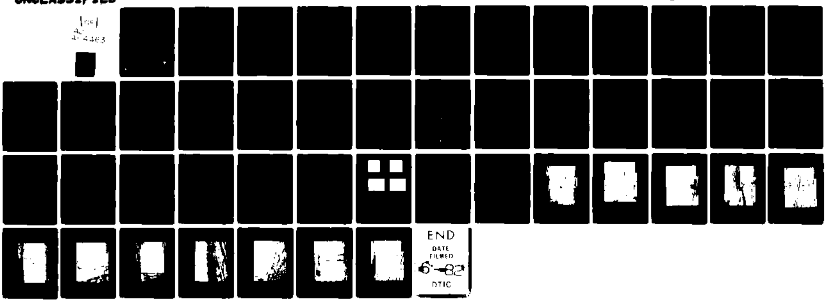

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EVALUATION OF SERVICE LUBRICANTS AND METALS

Final Technical Report

by

T Nonaka and A Cameron

April 1982

United States Army

EUROPEAN RESEARCH OFFICE OF THE US ARMY

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Six oils were provided by the US Army were tested to evaluate their lubricant properties under boundary conditions. Testing was on the High Frequency Reciprocating (HFR) device which has been developed at the Lubrication Laboratory, Imperial College, London.

Details of the HFR device and the test procedure are briefly explained and then discussed.

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Results of the oil tests are shown, and general properties of lubricants under boundary conditions are discussed. There is a considerable difference in the results which depends solely on the lubricant.

Results of three new oils are included and show good correlation with the results of a 200 hour Ford Tornado test.

Photographs of test wear scars are given and are similar to engine liner wear. This is explained and discussed.

SUMMARY

(High Frequency Reciprocating)

The report describes the first stage of the work. Six oils, sent from the US Army Fuels and Lubricants Laboratory, San Antonio, were tested in the HFR rig. This is a reciprocating friction machine, developed in the Lubrication Laboratory at Imperial College and described ~~here~~ in this report. It simulates the friction conditions found in piston rings of diesel engines.

The six oils produced different amount of polishing which is considered to be 3 body wear, ie. debris causes the polishing of the compacting surfaces.

A major finding is that polishing is very sensitive to temperature.

Since reliable data is not available to indicate the instantaneous interfacial temperature this must be found by comparing HFR results with full scale diesel tests. → ([illegible] p1473B)

For this reason close liaison with the US Army San Antonio Laboratory is most important.

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<u>NOTE</u> Total enlargement is given, as all photographs have been enlarged 2.75 times from the original negative. Photograph numbers and figure numbers are the same to allow easy cross reference.

INTRODUCTION

Diesel engine operating conditions have recently increased in severity and as a result cylinder liners experience a new form of wear, called bore polishing. This condition is characterised by large areas with a mirrored surface finish. Bore polishing of the cylinder liner gradually increases oil consumption, decreases engine performance and shortens the life of engine. In extreme cases it can lead to cylinder liner scuffing or scoring.

Some explanations of the mechanism of diesel engine bore polishing have been attempted but it is still not yet properly understood. It is, however, generally known that the lubricant plays an important role in determining bore polishing. Some test methods have been developed to evaluate lubricant effects but they normally use actual engines and are therefore, time and money consuming.

The aim of the current research programme was to develop a simple test method which can evaluate lubricant effects on diesel engine bore polishing and which also could contribute to understanding the role of lubricants under severe contact conditions.

BACKGROUND TO PROJECT

Some theories of the mechanism of bore polishing have been proposed. These can be summarised as follows:

1. Bore polishing is due to carbon particles being deposited either near the piston crown or packed round the rings. The carbon deposited near the piston crown may be introduced into the contact between piston rings and cylinder liner and as some forms are abrasive this can cause severe wear [1].

2. Due to high temperature and pressure at Top Dead Centre (TDC) some areas of the contact operate under boundary lubrication conditions. This can cause asperity interaction responsible for scuffing and wear [2]. Although it has been shown in the last few years that over most of the stroke the lubrication of a ring is mainly hydrodynamic [3].

3. Corrosive wear due to sulphur dioxide produced by the combustion processes. To prevent this dispersants are added to the oil.

The abrasive carbon particles in oils are not only produced by combustion but also by continuous heating of lubricating oils at high temperatures. The fuel in a combustion chamber can dissolve into the oil and may change its performance.

Corrosive wear processes can be considered to be due mainly to combustion products, however the composition of lubricant and fuel may also be important. The composition effects of lubricants and fuels can be considered as a problem of engine-fuel-lubricant compatability [4], this makes it difficult to understand bore polishing.

The culmination of many years work on the mechanism of EP and boundary lubrication carried out in the Lubrication Laboratory has led to the development of a test rig which can evaluate the performance of lubricants. As it uses a high frequency reciprocating motion it is called the HFR rig. A description follows on page 6.

It has been encouraging to note that HFR evaluation of lubricants in terms of bore polishing have been in good agreement with those obtained in standard diesel engine bore polishing tests. Although the HFR tests were carried out in air and not in a combustion chamber.

It has been established that the chemical layer whih prevents asperity interaction is controlled by the active ingredients in the oil and the formation of such chemical layer is largely dependent on temperature.

REQUIREMENTS OF TEST METHOD

For the purpose of evaluating lubricants in the context of diesel engine bore polishing, a test method has been designed as follows:

1. Since the temperature is so high, the surface temperature of the liner has been measured at 250°C [5], a rig had to have a friction pair operating at temperatures of this magnitude.

   The surface temperature of the ring is determined by both mean temperature and instantaneous temperature rise by friction. It is, however, very difficult to determine the effect of frictional heating, therefore the frictional heating should be kept small enough to be negligible.

2. The simulation device must operate in the boundary regime, excluding hydrodynamic effects as far as possible, because no wear or scuffing would occur in hydrodynamic lubrication.

3. Work in the laboratory has established that the chemical layer responsible for lubrication of contacting asperities can be removed after each contact. The protective layer has therefore to be built up between passes. The rate of formation of the layer is controlled by the reactivity of the active ingredient in the oil as well as the temperature [6]. These factors are all related by the well known Arrhenius expression which states that rate of reaction $\alpha \exp(-E/RT)$, with E the energy of the process, R gas constant and T absolute temperature. This means that both repetition rate and temperature must be the same in engine and test rig.

4. The test should use the actual components of the full scale engine under test, or parts cut from it in order to simulate actual conditions as closely as possible.

5. Estimation of wear amount after the test should be provided for.

DESCRIPTION OF TEST RIG

The High Frequency Reciprocating (HFR) friction device, used in this project is shown in Figure 1. The friction pair was immersed in an oil bath filled with the oil and which is heated electrically to the required temperature. The oil temperature is measured by a thermocouple placed close to the contact area. The rate of temperature increase is controlled by a microprocessor control unit, a standard heating rate of 7°C/minute was used.

One member of the frictional pair, the dynamic specimen, is held by a clamp at one end of a rod whose other end was attached to a vibrator. This is a 25 watt electrical "loud speaker" type device driven by an oscillator and amplifier.

A stroke of length ±½mm was used as standard throughout the test, to avoid serious friction heating. However, it could be varied continuously up to ±1.5mm. The frequency could be any value up to 200Hz, a value of 50Hz was used. The dynamic specimen was loaded against the static specimen by a weight suspended directly below the point of contact.

The oil bath, after careful cleaning, was held tightly in an aluminium block, which holds two 200 watt electrical heating rods. The aluminium block itself was mounted on a resilient mounting. Alternative mountings, eg Teflon pads have also been tried in an attempt to reduce resonance vibration.

A piezo-electric force gauge was used to measure the friction. Resonant forces naturally were seen in the output from the force gauge, these were reduced to a minimum.

The frictional force output via a charge-amplifier, presented on a cathode ray oscilliscope should be a rectangular wave. However a sinusoidal wave, whose amplitude was sometimes 30% of frictional force signal, was superimposed on the rectangular. This was due to an inertia force caused by the vibration of the base on which the force gauge is mounted. This superposition of sinusoidal wave was overcome by putting a large mass against one end of the test machine.

Electrical contact resistance between the frictional pair was measured to indicate the presence or absence of a film, preventing metal-metal contact. The existence of this protective film is considered very important in the action of zinc containing oils.

TEST PROCEDURE

The static test piece was a part of cast-iron cylinder liner 2.6cm x 1.5cm, CLA = 0.75μm. The dynamic specimen was a part of chromium coated rectangular scraper ring 20mm long, 0.5mm thick. The radius of the ring is slightly smaller than that of the liner, which allowed the contact area and pressure to be the same for each test consequently the results were reproducible.

The oil bath and a pair of test specimens were carefully cleaned in toluene then acetone, air-dried and assembled. Immediately after assembly, about 20cc of the test oil was introduced to immerse the static specimen. The clamp was then loaded against

the static specimen by a hanging weight suspended directly below the contact point.

The friction force output via charge-amplifier was rectified and recorded on a chart recorder, the electrical contact resistance was also recorded.

The oil bath was heated by electrical heaters from room temperature up to 250°C at 7°C/min. Heating was continued at 250°C so that total duration of the test was two hours.

For all results reported the following test conditions were used.

Load	8.9N (2lbf)
Frequency	50Hz
Stroke	±0.5mm
Heating Rate	7°C/min
Dynamic Specimen	Chromium coated scraper ring
Static Specimen	Cast iron cylinder liner
Test Duration	2 hours
Maximum Temperature	250°C

RESULTS

The friction and electrical contact resistance (ECR) results for base oil and six oils from US Army are presented in Figures 2 to 8.

Three curves are shown as functions of time. The top curve is electrical contact resistance, full scale is infinite contact resistance indicating the formation of either a hydrodynamic or thick chemical protective film. Zero contact resistance is metal-metal contact. High electrical contact resistances measured were not considered to indicate hydrodynamic under the conditions taken in this test.

The middle curve is friction force, shown as coefficient of friction (μ). The bottom curve is temperature.

Estimation of the amount of wear after a test has not yet been fully established. Visible remnants of the original honing marks on the wear scar sometimes indicated the amount of wear. These remnants were observed using both optical microscope (magnification x 40) and a scanning electron microscope (SEM). The photographs taken under SEM are numbered 2 to 8. The honing marks are diagonal. The four numbers at the bottom right hand side refer to actual length in microns of the white lines at the bottom, working distance (in cm) accelerating voltage in Kilo Volts and identification number respectively. Photograph numbers and figure numbers are the same to allow easy cross reference.

The surface profile of the wear scar was obtained with a Talysurf 4. The depth of the wear scar varied depending on the oil tested, however, it was difficult to estimate the amount of wear, as it was not constant along and across the scar. Three surface profiles of wear scars along the stroke are shown in Figure 12 from the tests using base oil 350 NS and AL-10722-L and AL-6856-L. An arbitarily classified of wear is given as severe, medium and slight. This is given in Table 1.

The results of three new oils tested are shown in Figures 9 to 11. As these oils had previously undergone a 200 hour Ford Tornado test, a comparison between the two test methods is possible. The oils are the two reference oils, CEC RL-47, CEC RL-48, and a commercial oil A. On the Ford Tornado test, CEC RL-47 gave 17% and CEC RL-48 45% bore polishing, the commercial oil A was in between these two. The surface profiles of the wear scars using these three oils are shown in Figure 13. The properties of oils RL 47, RL 48 and commercial oil A are shown in Table 2. A summary of all oils tested is given in Table 1.

Six surface profiles of wear scars along the stroke are shown in Figures 12 and 13. The differences of the depth of wear scar are definite, but may change across the stoke on each surface.

A characteristic of the surface profile of a wear scar is that the more severe the wear is, the smoother the surface profile. This is, however, still qualitative and difficult to quantify.

The order of the depth of wear in Figure 12 is Base oil > AL-10722-L > AL-6856-L. This corresponds to the estimation by observation of wear scars by the SEM. See photographs 2, 4 and 7.

The order of the depth of wear in Figure 13 is RL-48 > Oil A > RL-47. This is in good correlation with test results using actual engines.

Estimation of the wear amount by measurement of surface topography has not been well developed yet, although it is difficult to quantify, differences are usually apparent.

DISCUSSION

The electrical resistance was measured to indicate the rate of formation of a protective chemical layer, which is dependent on temperature, as described above. This can be divided into four regions depending on oil temperature.

I. Room temperature to 90°C

Some oils formed either chemical or hydrodynamic film in this region. A remarkable decrease in friction force was observed for several minutes after the beginning of the test, this increased again when the film decayed. Though the test did not continue long in this region, the surface profile changes quickly and this is important in determining surface profile at the end of the test.

II. 90°C to 160°C

The protective film formed at the very beginning of the test sometimes failed when the temperature reached about 90°C to 100°C and further formation of the film was not observed until the temperature had reached about 140°C to 160°C at which it is considered some EP additives begin to operate. In other cases the reverse is found.

III. 160°C to 220°C

Most of the oils tested formed protective films at a high temperature, above 160°C these usually decayed at 220°C to 230°C.

The start of film formation of any kind was accompanied by a slight increase in friction force similar to that observed at hydrodynamic film formation, however this decreased gradually when the film stabilised. See Figures 3 and 8.

IV. 220°C to 250°C

None of the protective films were maintained at temperatures higher than 230°C and friction force increased several minutes after the film decayed. This increase in friction force varied depending on the oil tested. The difference in friction curve at constant temperature of 250°C was considerable, though the reason for this is not known at present.

The increase in friction force was sometimes catastrophic and scuffing might occur in such cases. Scuffing marks across the stroke on some wear scars were observed under the optical microscope and SEM (photograph 4).

Only two oils formed films at 250°C several minutes after the previous films decayed. See Figures 3 and 4. A possible reason for this film formation not occurring immediately, but several minutes after the decay of the previous film, is that freshly formed metal surfaces are required for the reaction to take place. It was observed that after the decay of the thick film at 220°C the contact resistance continued to decrease as surface products were removed by rubbing and then the new film began to form. It is considered necessary for there to be some kind of surface process which can prevent metal-metal contact, even when the monitored contact resistance is almost zero, otherwise friction always results in catastrophic scuffing or scoring; the higher the friction, the larger the area of reactive metal exposed, so this is a kind of positive feedback mechanism.

The process to prevent metal-metal contact increase as the decrease in the thickness of surface products and is stable when removal of the products by rubbing and the rate of the process are balanced. The friction, therefore, needs to be analysed as a stability problem.

Figure 15 gives a typical force and contact resistance trace on an oscilloscpe and Figure 14 is from the pen recorder. In this test the oil bath was moved a few microns thirty minutes after the start of the test and the contact resistance then became zero. It was noticed that the resistance recovered gradually to its previous value. Such an ability for a contact to repair the damage to the surface film, which may be caused by the presence of debris in the oil, could well be important for antiwear effectiveness. Wear or scoring in boundary lubrication, therefore, should be considered as a dynamic stability problem.

Test oil performance was classified in three grades according

to the film formation for each temperature region described on the previous page (1: good, 2: medium, 3: poor). This is included in Table 1.

The amount of wear was estimated by observing the wear scar under the optical microscope and SEM. This is classified into three groups by observing the visible remnants of the original honing marks (1: slight, 2: medium, 3: severe).

The extent of scuffing, recognised as sudden increase in friction force at constant temperature at 250°C, is shown in Table 1 separated in three classes (1: slight, 2: medium, 3: severe). Wear of cylinder liner affects both engine life and performance, therefore not only the absolute amount of wear but also the mechanism of wear needs to be considered. The same is also true of scuffing.

Scuffing marks are observed on a wear scar as a local dragging of the surfaces. It looks like a wave across the stroke (photograph 4). The scuff marks may be diminished with subsequent abrasion (photograph 5). However the cyclic and sudden increase in friction force during the constant temperature period at 250°C indicated scuffing (Figure 5).

Examination of actual enigne liner surfaces has always indicated that the main wear takes place near TDC. It is usually ascribed to fine abrasion [7], where the contact pressure from the ring is highest. Photographs 2, 5, 6 and 7 show that this kind of abrasion is reproduced by this test, and appears as parallel grooves along the stroke. It is, however, difficult to tell whether this is 2 body abrasion, hard chromium coated piston ring against case iron liner or 3 body abrasion, whatever the third body may be.

It is often said that bore polishing is caused by the hard carbon from the carbon deposited at the piston crown. It is, however, suggested that in the case of cast iron hard phases in the metallurgical microstructure (such as phosphides and carbide) generate abrasive particles, when they are broken up. These hard phases also provide the main resistance to abrasion [7]. It is also shown that where corrosion attacks the pearlite structure of the cast iron, it tends to remove preferentially the small regions of ferritic material, in the pearlite. This leaves carbide flakes standing proud in a brittle structure, like a pack of cards. This structure can be readily broken up by the movement of the piston ring releasing carbide into the system. Corrosion, therefore, plays a more important role in wear mechanism in engines operating on high sulphur fuel, though corrosion itself causes the least amount of wear in comparison with other types of wear.

Corrosive pitting is observed on the wear scar surface (photographs 3a and 6a), especially in light areas. The change in darkness suggests the absence or presence of surface films produced by either oxidation or chemical reaction with the additives. This suggests the conclusion that corrosion occurs without combustion using high sulphur fuels. These generate acid material from the oxidation of the sulphur and is controlled by chemical products on the surface which in their turn are changed by the oil itself.

Photographs 2a and 5a, using base oil and AL-7172-L respectively, show the boundary of virgin surface and the wear scar. The left hand side is virgin surface and the right is the wear scar. The worn surface is rough on photograph 2a but fine and smooth on photograph 5a, although the amount of wear for both specimens was similar. This suggests a difference in the wear mechanism but this suggestion has not yet been fully worked out.

The fact that chromium was found by X-ray microanalysis, only on the plateau of the liner, but not in the cross honed groove, suggests the chromium on the piston ring was transferred to the cylinder liner. This gives an explanation of the cyclic and the sudden increase in friction force. This explanation is:

1. Scuffing occurs at the highest peaks of the asperities, followed by a sudden increase in the friction force.

2. As scuffing deforms the highest peaks the number of asperities engaged in contact increases and this reduces the contact pressure shared by each asperity contact. Consequently scuffing is terminated and the friction stabilises.

3. Scuffing, in the case of ferrous materials, forms a thin layer of very hard transformed material on the surface but will spall off, and scuffing begins again.

The metallurgical properties of the metal surface plays an important role in wear mechanisms so that is is insufficient to study lubricants <u>without</u> taking account of the test metal. It is, therefore, necessary to examine the material combination. This is quite simply done with the HFR.

CONCLUSIONS

The tests show that the performance of oils changes significantly in the region 200°C-250°C. The oil's performance therefore is strongly influenced by the exact temperature. The effective operating temperature of engines, as it is almost impossible to measure, can only be found by working backwards from the actual engine performance to tests on this HFR machine.

The wear produced on the test shows similarities to the worn surfaces on the actual engine cylinder liners. The use of the actual components from the full scale engine under test is considered to be absolutely necessary as metallurgy has a decisive influence on the wear mechanisms.

A further consideration is the effect of sulphur in the fuel. Work which has just come to our notice from the French Institute of Petroleum in the form of a yet unpublished report, shows that sulphur in the fuel plays a very important role in the high bore polishing oil RL-48. The influence of sulphur in the fuel on bore polishing with the oil that gives low polishing (RL-47) is not at all marked. The incorporation of this most important finding is now under active consideration.

Difficulties have been encountered in evaluating lubricants by this test method. The problems in developing a test method to evaluate lubricants using the HFR are summarised as follows:

1. To estimate the composite effects of lubricant and fuel.

2. It is difficult to determine the working condition of an actual engine, therefore there are problems in reproducing them accurately.

3. History of surface profile changes during the test and this can affect the final result.

1. Composite effects can affect the following:
   . production of abrasive carbon
   . attack by corrosive chemicals on the metal surface, for example oils themselves are normally over basic.
   To take account of these two the presence of combustion products is essential. It is therefore proposed to introduce sulphur into the contact area. This will be done either by sulphuric acid or by leading in exhaust gases.

2. The correlation of test results on the HFR rig with those from standard engine tests may be poor when the critical temperature of the actual engine differs from the maximum temperature of the test. Operating temperatures of 200-230°C are critical with any oils which have EP additives.

3. It is necessary to estimate the effect of surface profile on friction film formation and wear. This has not been fully analysed yet.

GENERAL CONCLUSION

This apparatus produces wear scars indistinguishable from those found in engines, and shown for instance in reference [6]. All the figures indicate that temperature is a very important factor in the process. No reliable data is available to show what is the instantaneous <u>interfacial</u> temperature between ring and liner. To obtain meaningful correlation it is necessary to vary the conditions of the HFR test, ie time and temperature, so the HFR and diesel engines correlate. To do this very close co-operation is needed between the Imperial College laboratory and San Antonio.

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APPENDIX 1

Individual tests on one base oil, six oils supplied by US Army, two reference oils and one commercial oil.

Base Oil, Figure 2, Photograph 2

Film formation was poor at all temperatures. The friction force was very high and was almost twice as high as any other oil tested and unstable at 250°C. This resulted in severe wear.

AL-6855-L, Figure 3, Photograph 3

Film formation was observed at all temperatures even at 250°C though this is not often seen. The friction force at 250°C was the lowest of all the oils tested. This consequently led to minimal wear.

AL-6856-L, Figure 4, Photograph 4

The performance of this oil was similar to AL-6855-L except more scuffing marks and traces of metal-metal contact were observed on the wear scar.

AL-7172-L, Figure 5, Photograph 5

Film formation was very poor. Friction force was very high and unstable at 250°C. The wear was severe. This oil's performance is judged to be the worst of the six US Army oils.

AL-8924-L, Figure 6, Photograph 6

Film formation was poor at both low temperatures and 250°C. The friction force was high and unstable at 250°C. The wear was severe, but less so than seen in the AL-7172-L test, as the higher electrical contact resistance and the more stable friction suggests.

AL-10513-L, Figure 7, Photograph 7

The performance of the oil and the wear obtained was quite similar to oil AL-8924-L.

AL-10722-L, Figure 8, Photograph 8

Film formation was similar to AL-10153-L oil test. The friction force was stable at 250°C though the value was higher than AL-6855-L and AL-6856-L oils. This resulted in medium wear.

CEC RL-47, Figure 9

Film formation below 230°C was stable and 'thick' film formation was observed at constant temperature 250°C. The wear was minimal.

CEC RL-48, Figure 10

The film formed at lower temperature and at 250°C but was poorer than with RL-47. The friction force increased sharply after the film decayed at 230°C. As a result the wear was more severe than that found in the RL-47 test.

Commercial Oil A, Figure 11

The ability to form surface films wasbetween that of the previous two. The friction force was higher but was quite stable.

The wear was also in between the wear of the previous two oils.

NOTE AL-4855-L was the best of six oils provided by US Army and the performance was similar to reference oil CEC RL-47, which produced 17% bore polishing on the standard Ford Tornado 200 hours test.

APPENDIX 2

Detailed description of photographs.

Photograph 2

Wear scar on base oil 350 NS test. The direction of sliding is parallel to the shorter side. The visible remnants of honing marks, which are ±12½° to the long side of the photograph, are few and this is considered to indicate severe wear.

This wear is characterised as evenly abraded grooves and they are parallel to each other. Abrasion was observed on another wear scar but was finer than this.

The large area of shallow pit on the right hand side of the photograph can be neglected. It is an artifact initiated by two deep cross hone lines crossing.

Black marks, like leaves, show graphite in the cast iron.

Photograph 2a

This shows the boundary of virgin surface and the wear scar (base oil 350 NS). The left hand side is virgin surface and the right hand side is the wear scar. The direction of sliding is parallel to the long side of the photograph. The boundary is just precipitous and cliff like. There are two wave-like bright lines just above the panel where the numbers are written, at right angles to the sliding. These may be traces of scuffing.

A crack is on the boundary just above the middle of the photograph. These defects, which appear as surfaces dragged by scuffing or as cracks often are at right angles to the sliding direction.

Photograph 3

Wear scar on AL-6855-L oil test. The wear is slight and there are few evidences of scuffing. This means that a chemical film has prevented metal-metal contact. This is expected from the high electrical contact resistance and the low friction force shown in the recorder traces.

Photograph 3a

Surface of previous wear scar at 200 times higher magnification is shown here. There is a honing mark, diagonal to the sliding direction, and parallel to the small side of the photograph. The edge of the honed groove is deformed into the groove by the sliding. The small pits (especially on light coloured surface) are etched by corrosion. Otherwise the surface is quite smooth and the difference in colour, light and dark, indicate areas where the surface film has formed. Whether a light colour indicates absence or presence has not yet been determined.

Photograph 4

Wear scar on AL-6856-L oil test. Wear is slight but more metal-metal contact has occured here than in the AL-6855-L oil test. The wave-like line perpendicular to sliding direction are areas of dragged and slightly raised surfaces caused by local scuffing of asperities. No sudden increase in friction force during the test was observed.

Photographs 5, 6, 7, and 8

Wear scar on AL-7172-L, AL-8924-L, AL10153-L, AL-10722-L oil test respectively. The surfaces are quite similar to each other. The mechanism of the wear is fine abrasion, finer than that on the base oil test. The differences of the colours once again suggests the formation of a surface film. There is no definite evidence of scuffing, though the sudden increase in friction force indicated that scuffing occurred. This is because the scuffing marks have been removed by the severe abrasion.

Photograph 5a

This shows the boundary of the wear scar on the AL-10722-L oil test. The left hand side is virgin surface and the right hand side is wear scar.

This wear is also abrasion but quite different from photograph 2a. There are some charged products on the surface, which were not found in the base oil test. The surface of the wear scar is much smoother than that on the base oil test.

Photograph 6a, 6b

There is a band of grain like particles on the boundary of the wear. The upper part of the photograph is wear scar. A detailed picture of this band at higher magnification is given in photograph 6b. The material shown in the photograph is not yet identified. There are some corrosive pits, especially on light coloured bands on the wear scar, and are the same as those seen in photograph 3a.

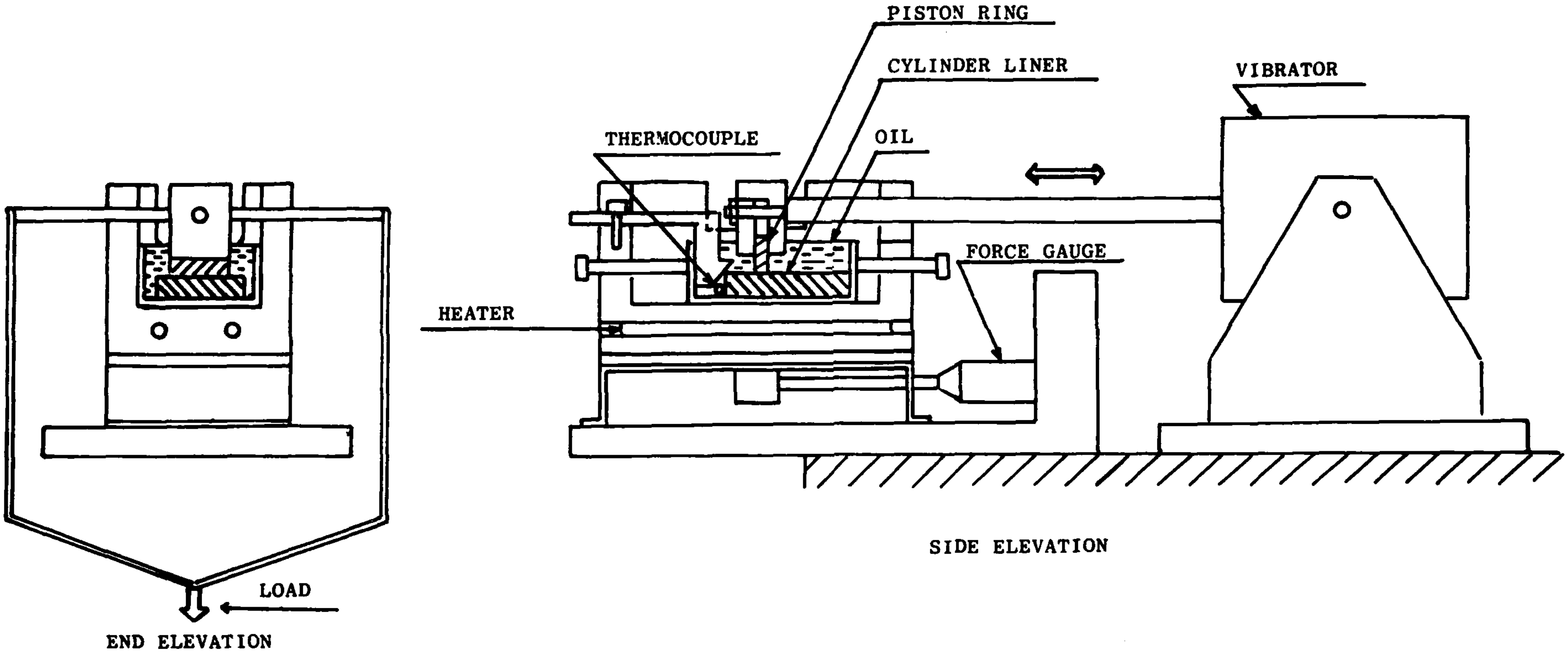


Figure 1 Diagram of High Frequency Reciprocating Rig

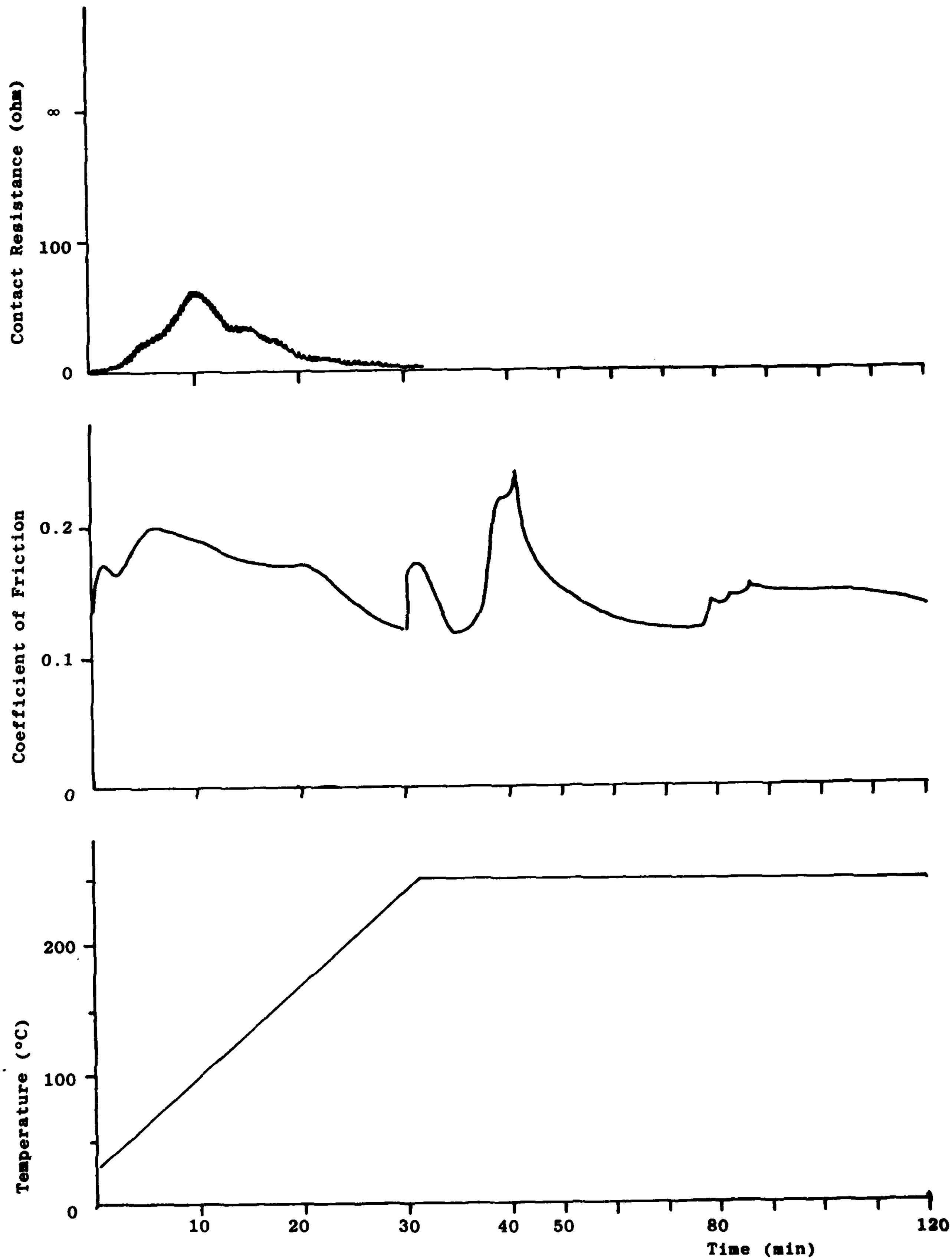


FIGURE 2 350 NS Base Oil Test

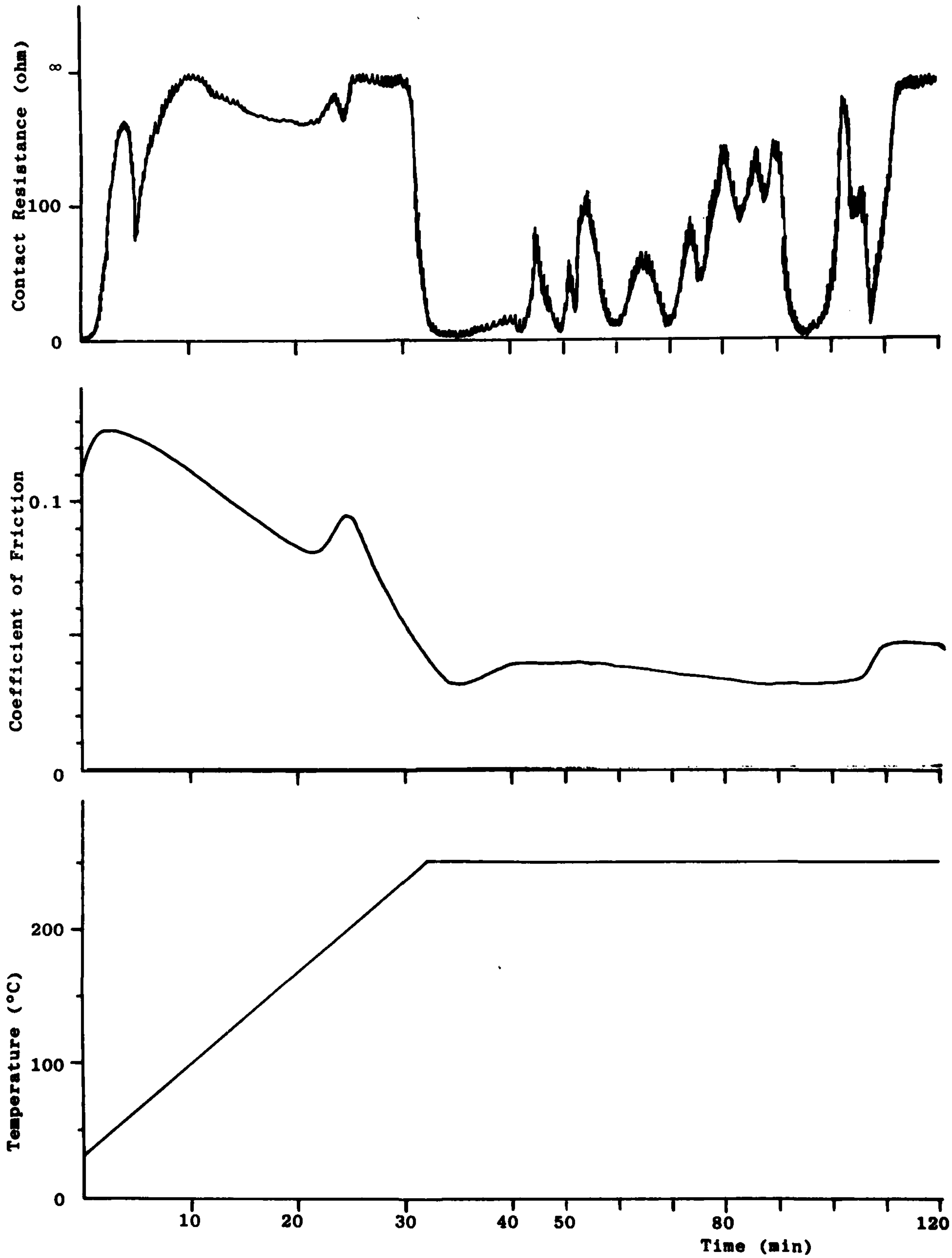


FIGURE 3 AL-6855-L Oil Test

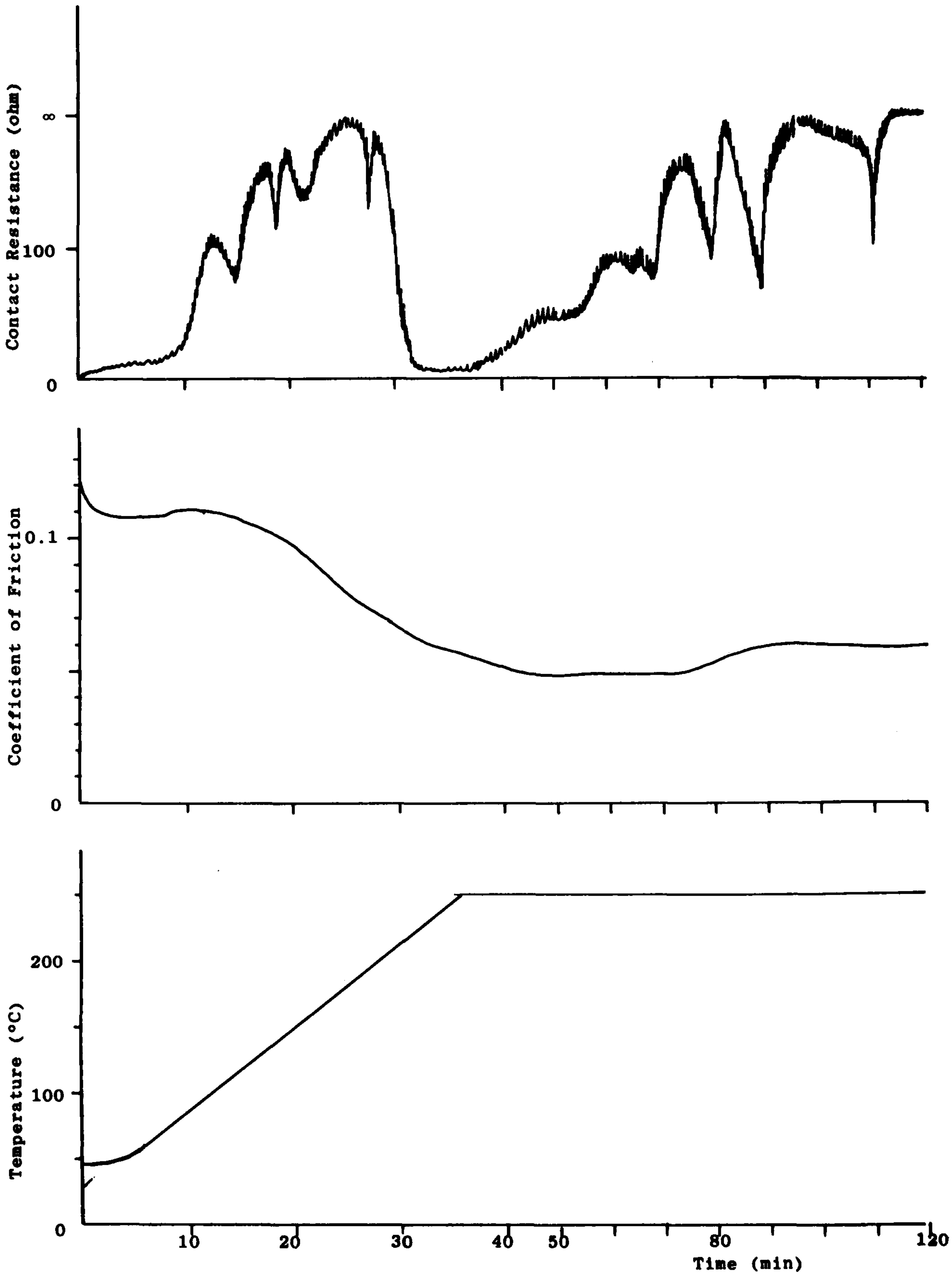


FIGURE 4 AL-6856-L Oil Test

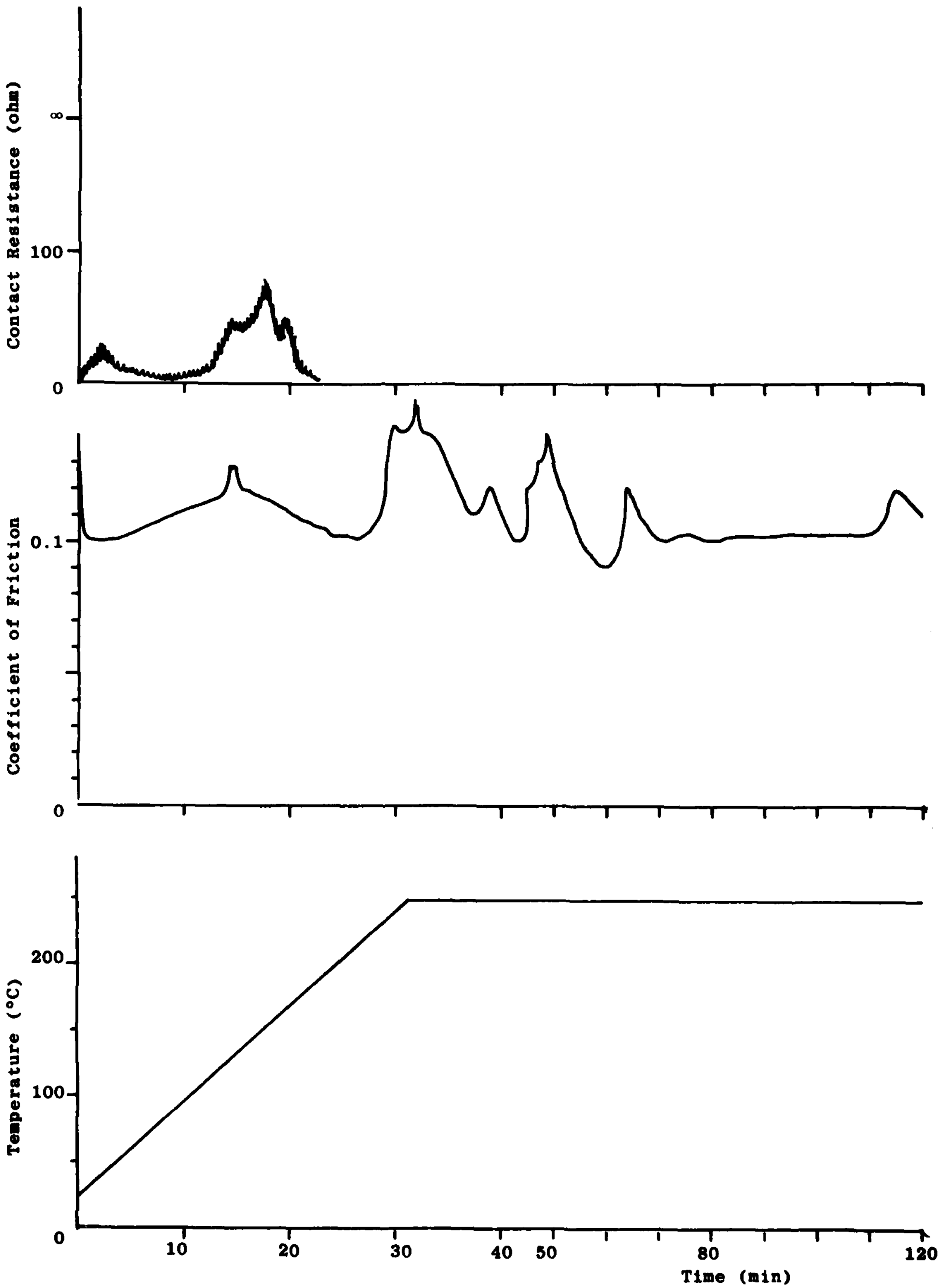


FIGURE 5 AL-7172-L Oil Test

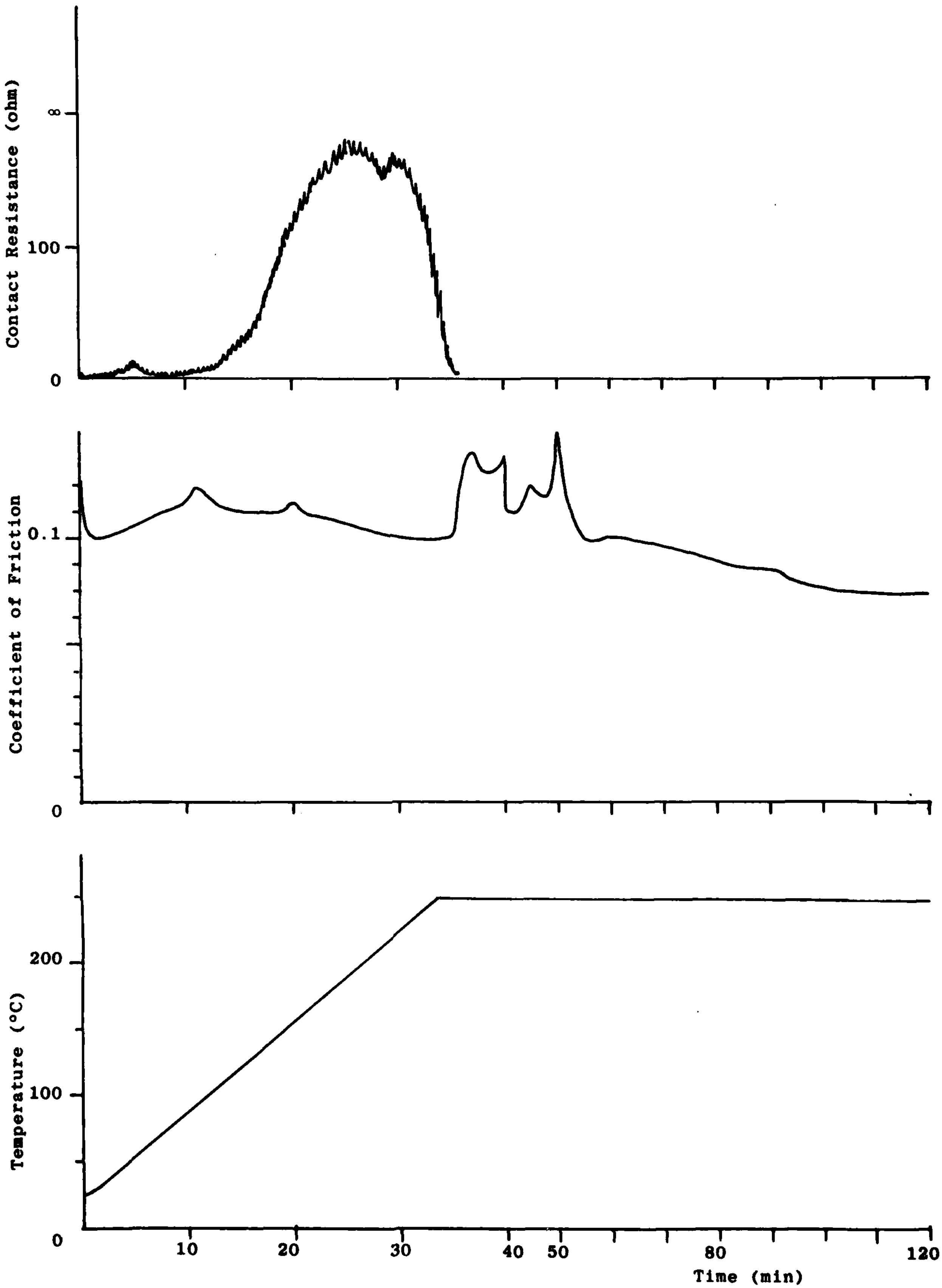


FIGURE 6 AL-8924-L Oil Test

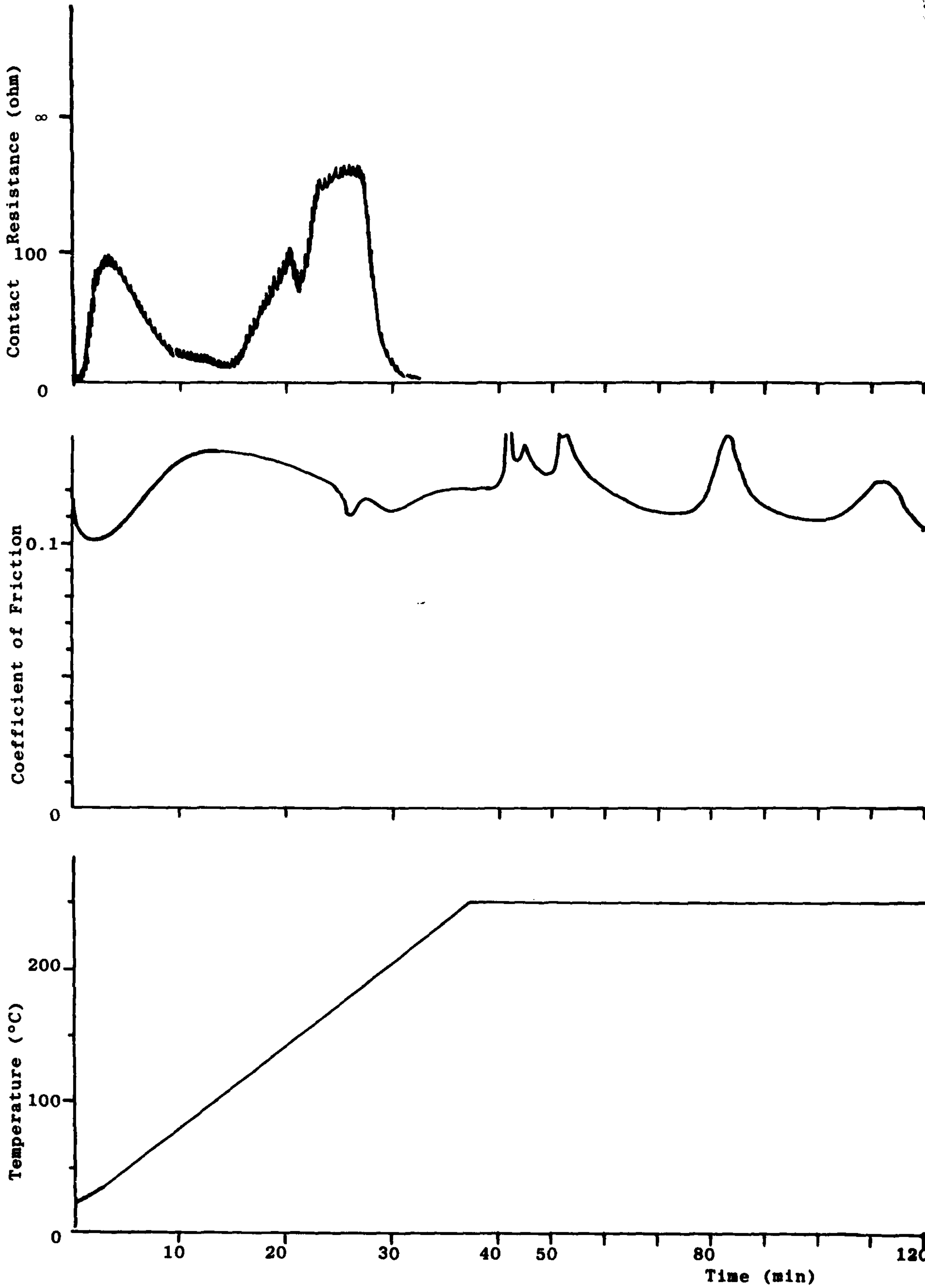


FIGURE 7 AL-10153-L Oil Test

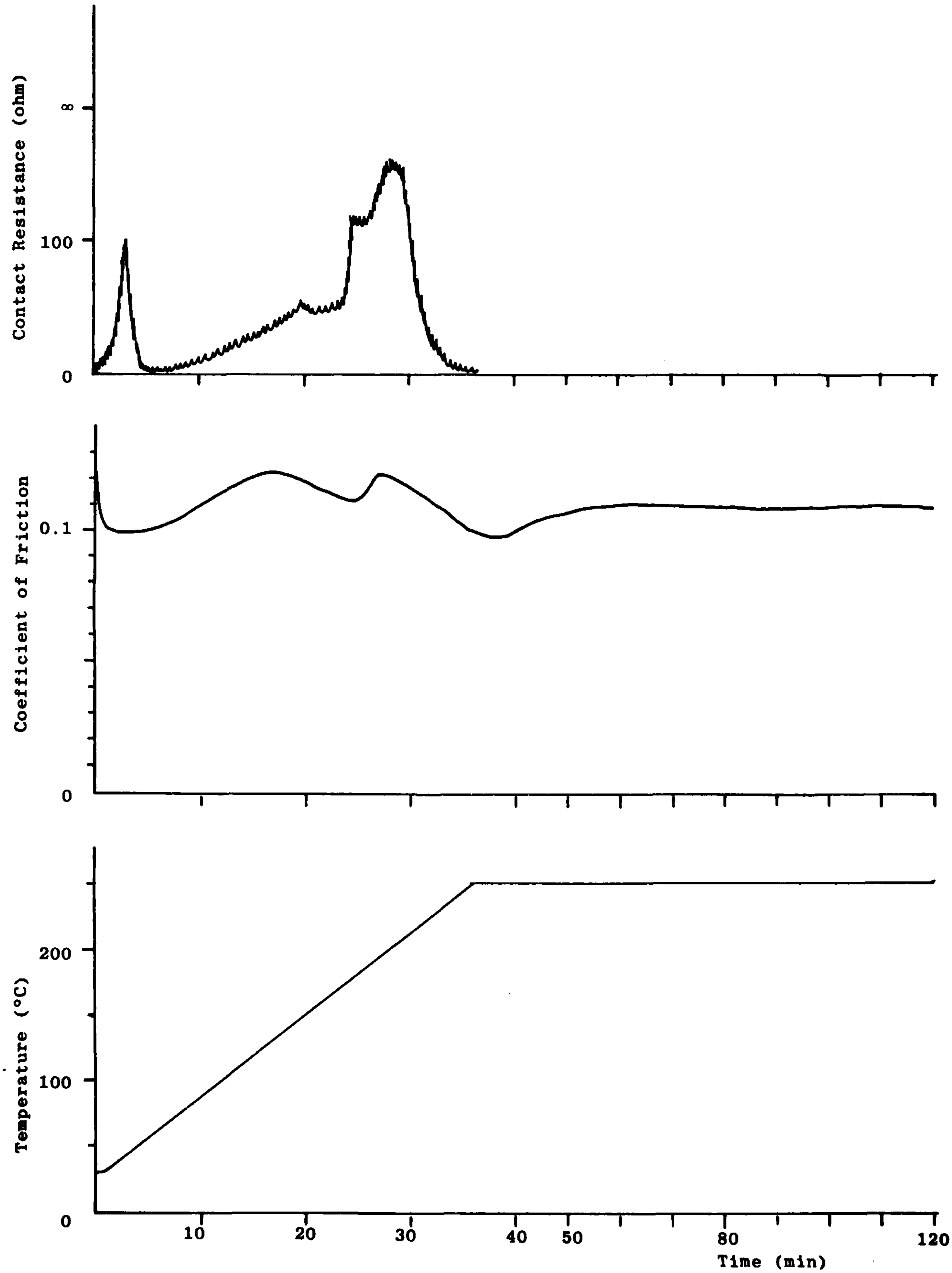


FIGURE 8 AL-10722-L Oil Test

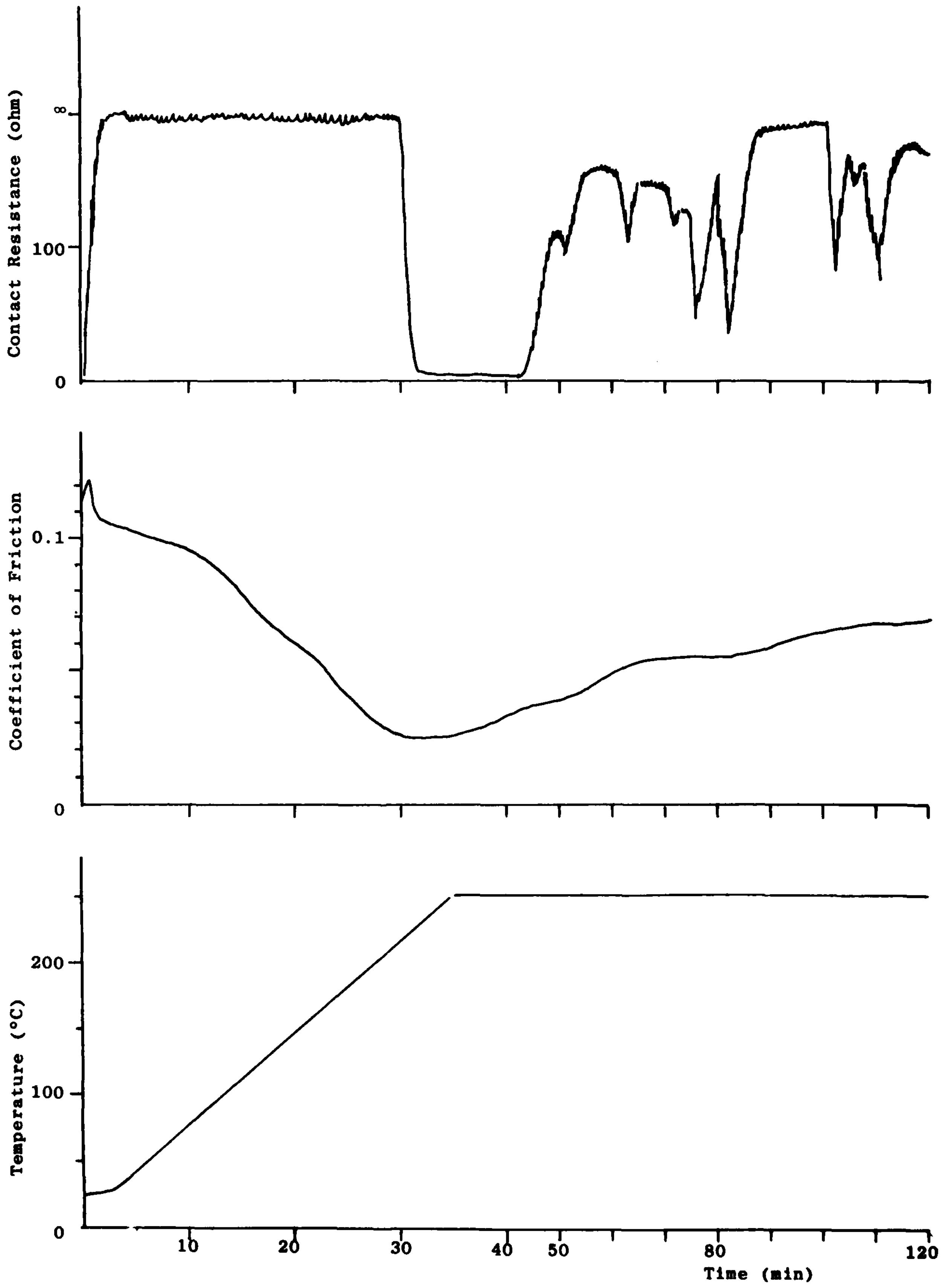


FIGURE 9 CEC RL-47 Oil Test

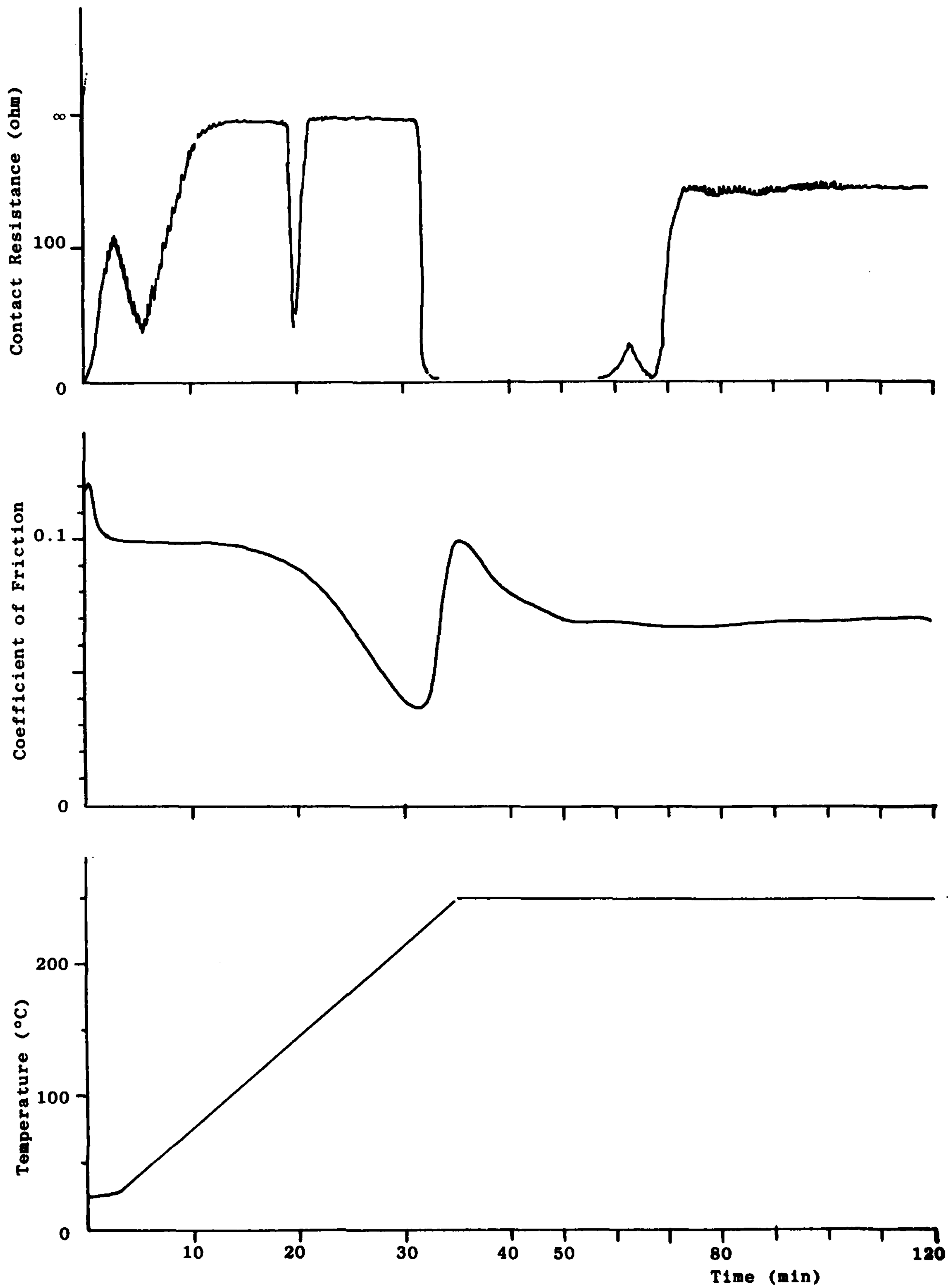


FIGURE 10 CEC RL-48 Oil Test

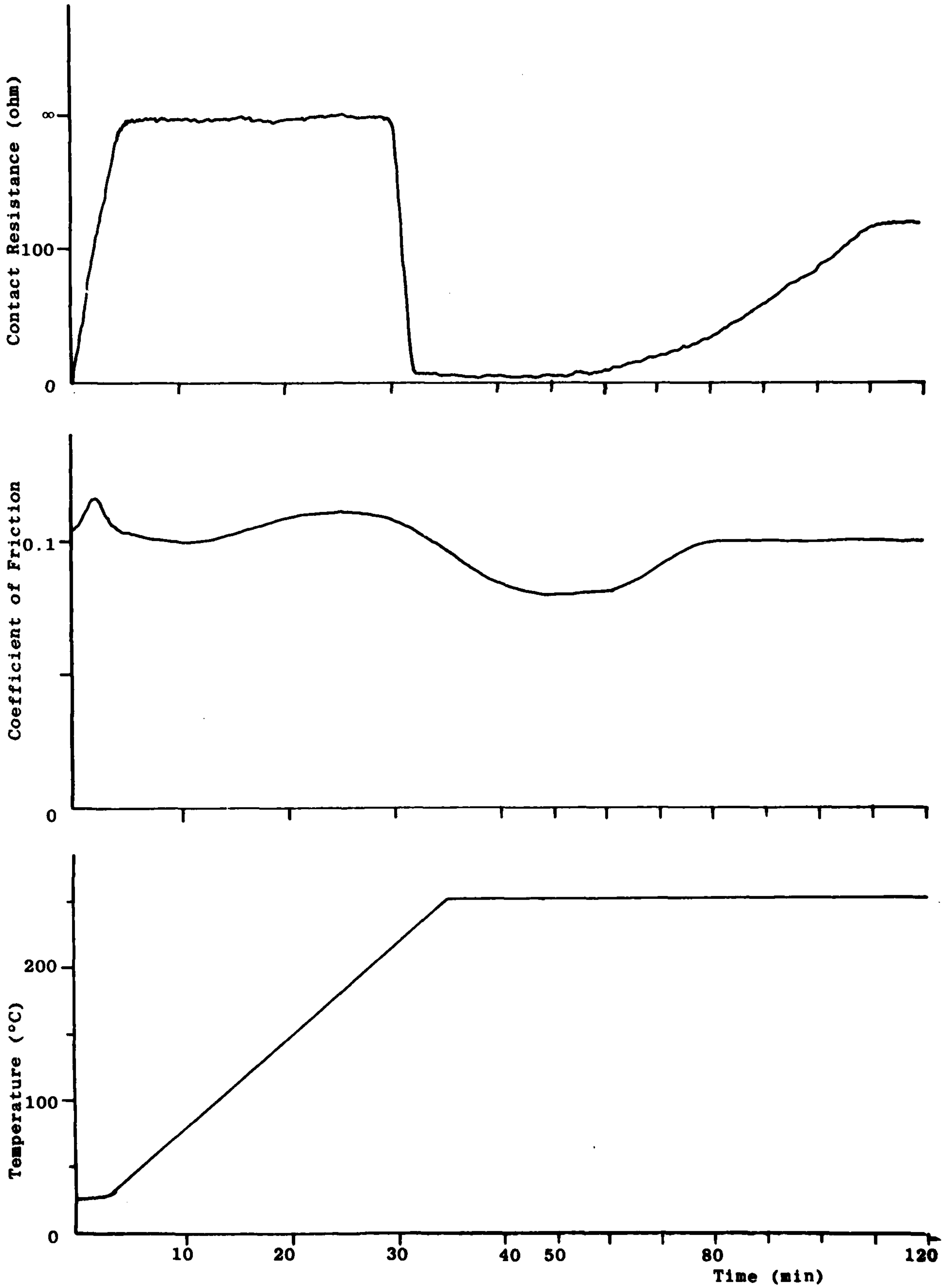


FIGURE 11 Commercial Oil A Test

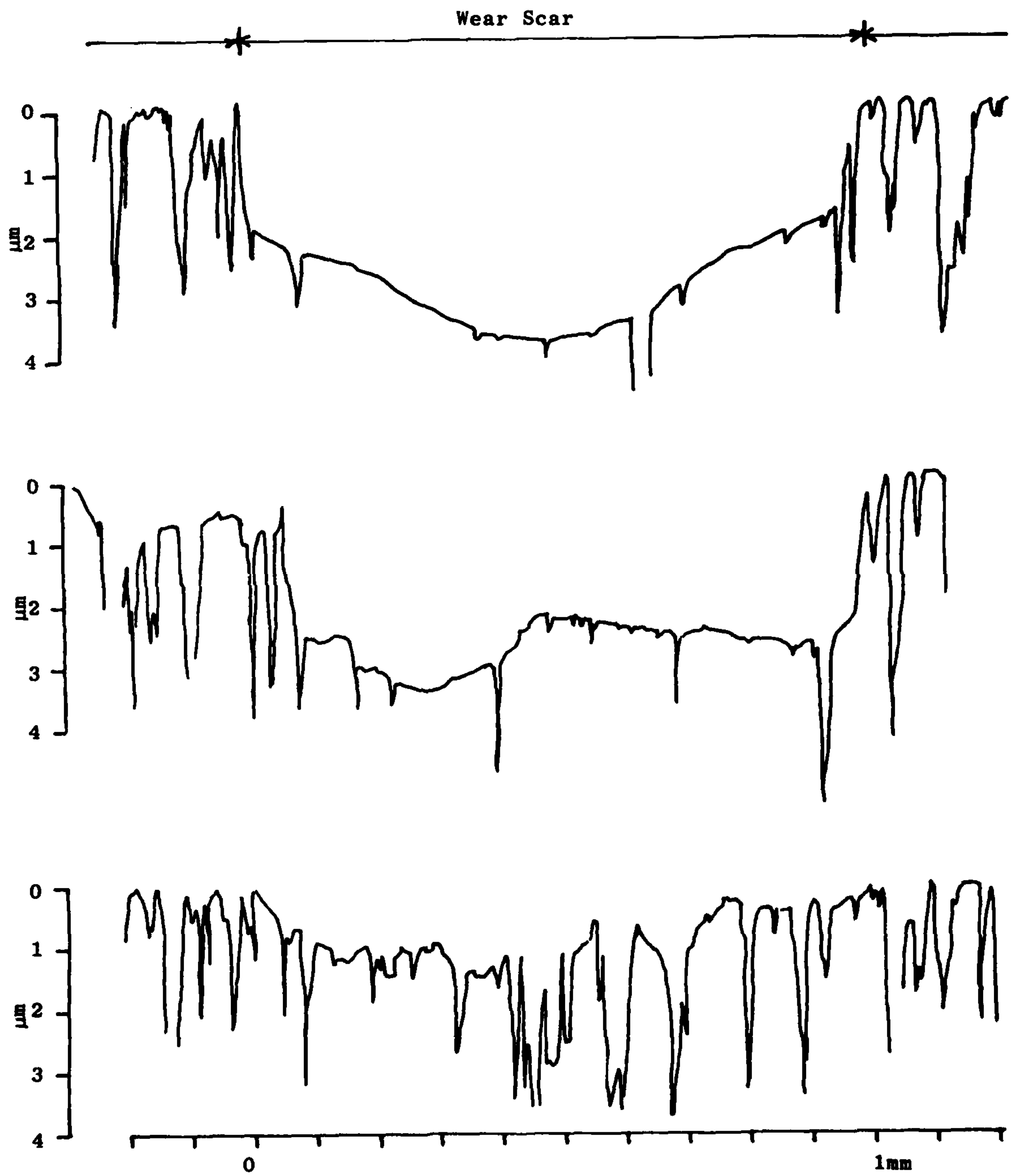


FIGURE 12 Surface Profile of Wear Scar

Top - 350NS Base Oil Test
Middle - AL-10722-L Oil Test
Bottom - AL-6856-L Oil Test

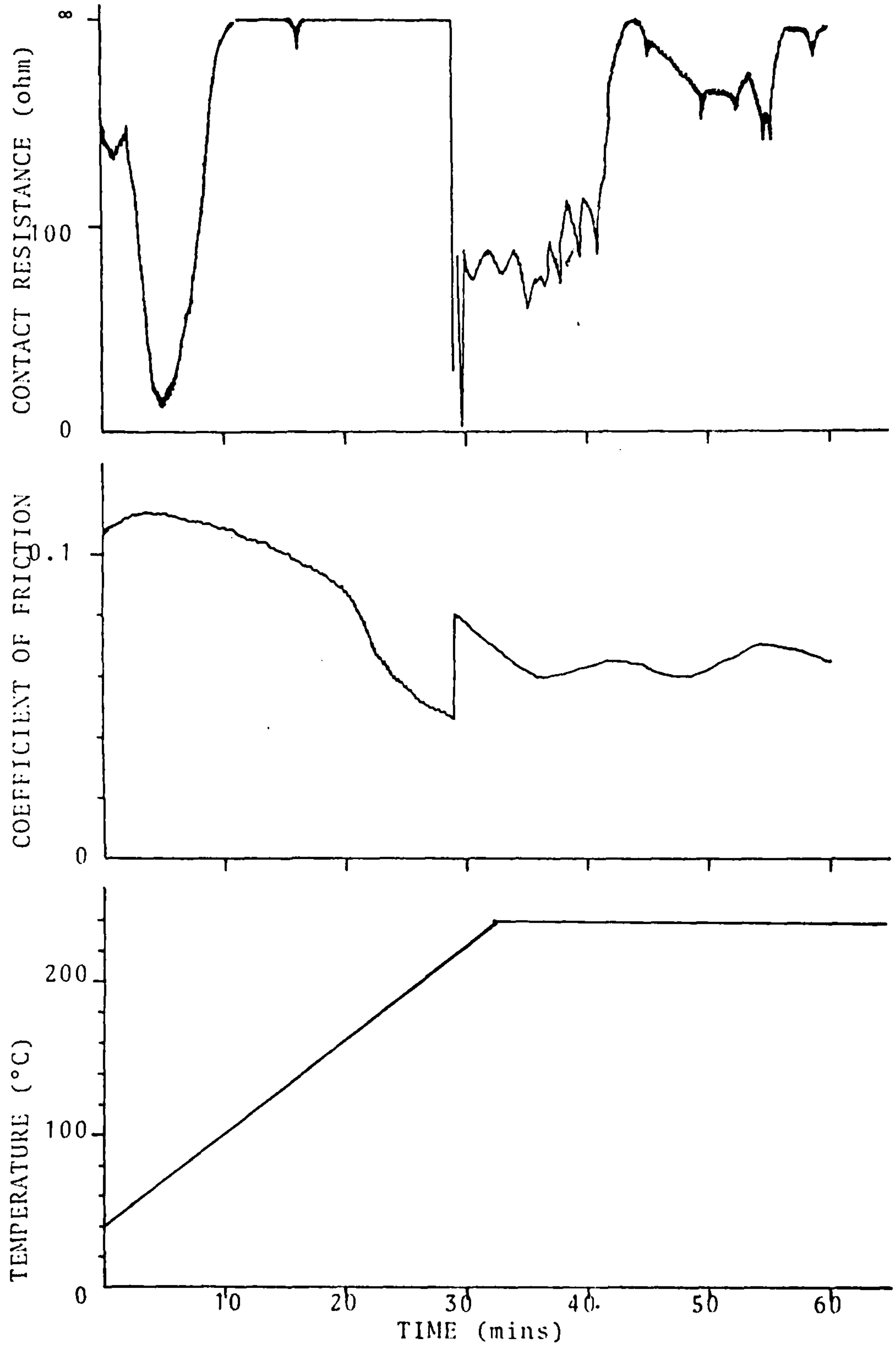


Figure 14 AL-6856-L Oil Test,
Load 8.9N, Stroke ±0.5mm, Frequency 50Hz

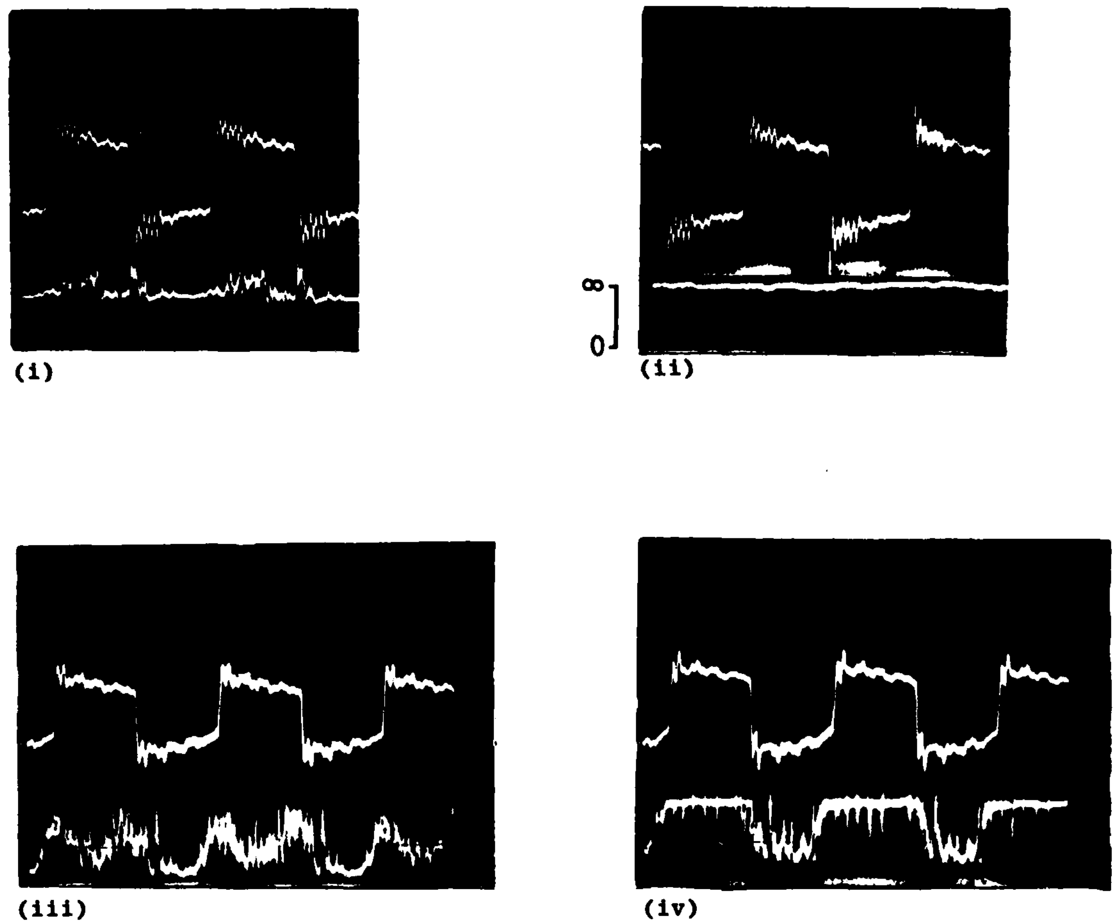


Figure 15 Friction and Contact Resistance During the Test are shown in Figure 14. Friction Top Line, Resistance Bottom.

Time after start,

(i) 5 minutes, electrical resistance begins
(ii) 10 minutes, electrical resistance begins
(iii) 30 minutes, resistance falls after bath movement
(iv) 55 minutes, resistance re-established

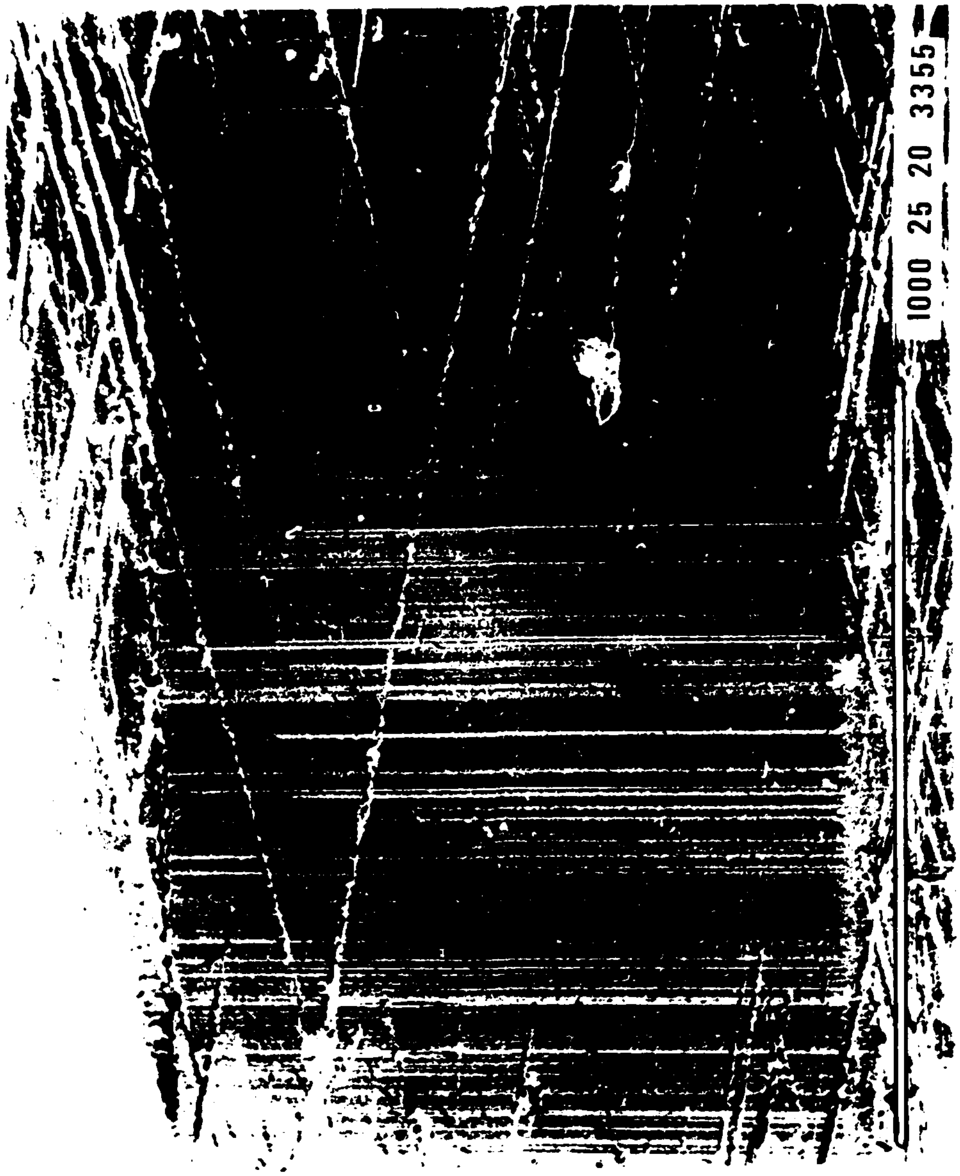
OIL	TEMPERATURE REGIONS				WEAR	SCUFF
	I	II	III	IV		
BASE OIL	3	3	3	3	3	3
AL-6855-L	2	1	1	2	1	1
AL-6856-L	3	2	1	2	1	1
AL-7172-L	3	2	3	3	3	3
AL-8924-L	3	3	1	3	3	2
AL10153-L	2	3	1	3	3	3
AL-10722-L	2	3	1	3	2	1
RL 47	1	1	1	1/2	1	1
RL 48	2	1	1	2	2	1
Oil A	1	1	1	2	1	1

TEMPERATURE	I	room temperature - 90°C
	II	90°C - 160°C
	III	160°C - 220°C
	IV	220°C - 250°C

TABLE 1 Classification of Test Oils

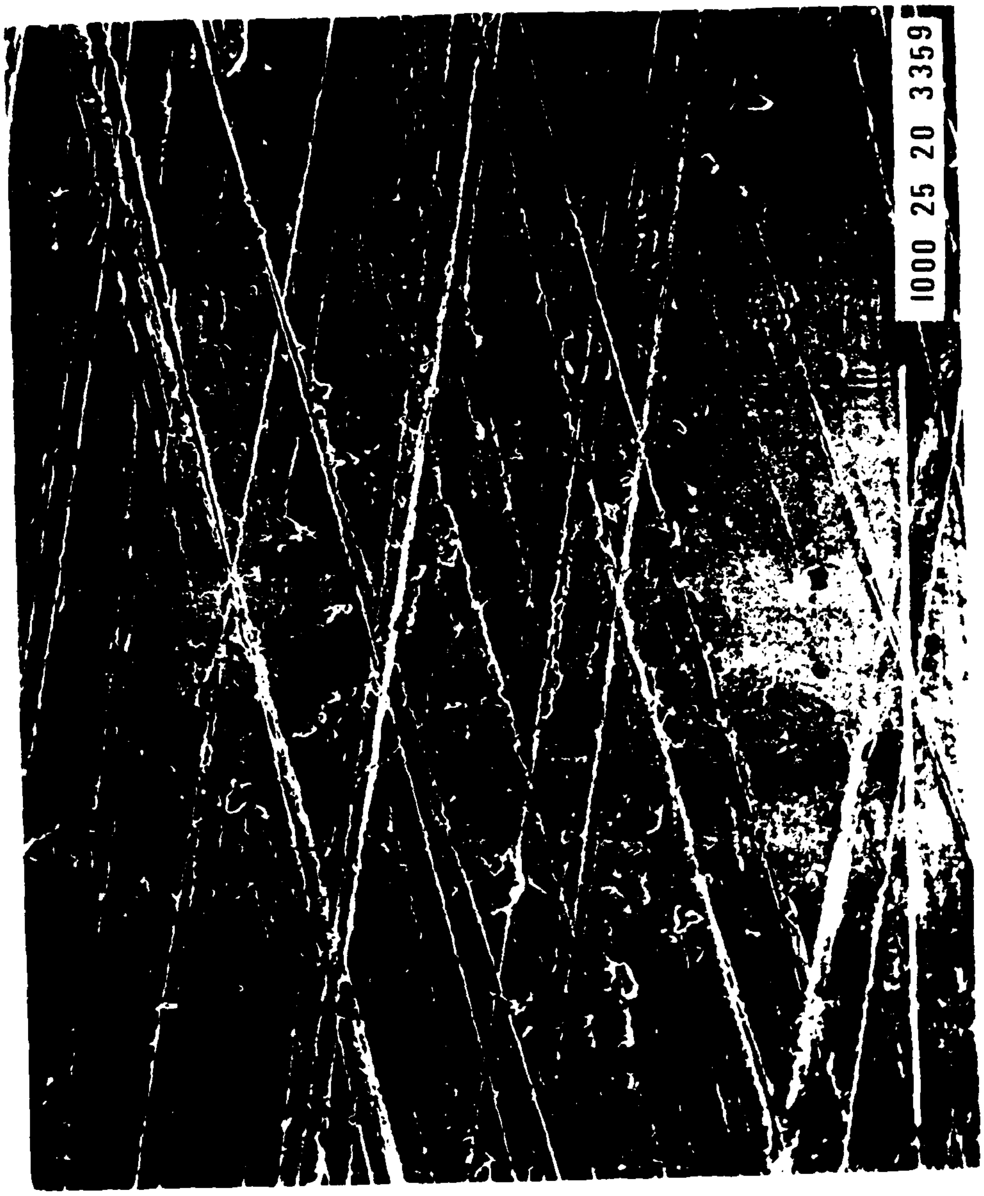
		Method	CEC RL-47	CEC RL-48	Oil A
Viscosity cSt	40°C	ASTM D 445	102.2	65.31	102.1
	100°C	ASTM D 445	13.40	8.61	14.60
Viscosity Index		ASTM D 2270	129-130	102-103	148
Ash	wt%	ASTM D 482	1.41	0.95	
Sulphate Ash	wt%	ASTM D 874	1.88	1.27	
TAN	mgKOH/g	ASTM D 664	2.62	3.16	2.92
TBN	mgKOH/g	ASTM D 664	17.5	9.1	13.8
Metal analysis ppm	Ca		5499	3184	5050
	Zn		1249	1594	1160
	P		1392	1468	1060

TABLE 2 Properties of Test Oils



Photograpl

Photograph 2a



Photograph 3

Photograph 3a

Photograph 4

Photograph 5

Photograph 5a

Photograph 6

Photograph [illegible]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